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Study of the Quantum Efficiency of Semiconductor Quantum Dot Pulsed Micro-Laser

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Abstract: The interaction of the cavity electromagnetic field with the two-level emitter is described by cavity quantum electrodynamics (CQED). A pulsed micro-laser is an array of semiconductor quantum dots (QDs) embedded in an optical micro-cavity. This is one of the basic tools of quantum information technology. In this study, the energy eigenvalues variations and the quantum efficiency of a micro-laser system includes a QD with a decay rate of 0.8μeV embedded in the different micro-cavities, were investigated. The results show that with the increasing coherent interaction rate of micro-laser system, the energy eigenvalues variations of this optical system also increase. The quantum efficiency for this nano-optical system was studied. The results show the smaller micro-cavity decay rate, the higher quantum efficiency at smaller coherent interaction rate. Then, the optimal value of the micro-cavity decay rate was obtained in order to achieve the maximum quantum efficiency. The calculation results showed that the highest quantum efficiency occurs for optical parameters γ_a=0.8μeV, g=95μeV, γ_c=177.7μeV, and η_{max}=0.991.

Keywords: Quantum Efficiency, Micro-Laser, Quantum Dot, Micro-Cavity, Energy Eigenvalues

1. INTRODUCTION

One of the most important quantum optics systems is the two-level system. The two-level system is the simplest quantum system used to describe the dynamics of optical quantum systems. A two-level quantum system in two-dimensional Hilbert space is described. Two-state quantum systems include the polarization of a single-photon with two states of horizontal polarization and vertical polarization, or the electron spin of a quantum dot (QD) with two states of up or down.

Various cavity quantum electrodynamics (CQED) systems such as a color center in diamond [1], single ions in traps [2], single molecules [3] and QD [4-

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6] based on atom-like emitters have been studied. QDs are semiconductors that have nanometer dimensions in all three dimensions, so they are called zero-dimensional structures. Due to the quantum confinement effect, as the size of QD decreases, their energy bandgap also decreases. This effect occurs when the size of the QD is smaller than the Bohr radius. In other words, this effect is observed when the particle size is very small and in the order of electron wavelength. In QDs, electrons occupy discrete positions of energy, so quantum dots are very similar to real atoms and in quantum mechanics they are also called artificial atoms. QDs are used in various sciences and technologies, including optoelectronic systems [7-11], medicine [12], imaging [13], solar cell [14] and have even recently been used to study Covid-19 [15]. QDs are also used in single-photon sources, the basic tools of quantum information science [16, 17]. QDs are used to fabricate micro-lasers.

By embedding an array of QDs in a micro-cavity, a pulsed micro-laser system is fabricated. In this quantum photonic system, these QDs with the surrounding micro-cavity must be in the strong coupling regime [18]. Figure 1 shows a schematic of QD pulsed micro-laser. These optical systems are usually fabricated by high-resolution electron-beam lithography and plasma reactive ion etching. Micro-lasers have many applications in the quantum information, quantum cryptography, etc. [19, 20]. More details about the fabrication of micro-lasers are given in [21].

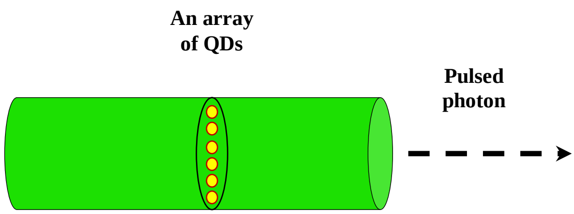

Figure 1. The schematic of QD pulsed micro-laser

Quantum efficiency is one of the most important parameters of CQED systems. In many applications such as quantum information processing, high quantum efficiency micro-lasers are needed [22, 23].

In [19], Pierce Munnelly et al. presented self-assembled InAs QDs embedded in micropillar cavities as a novel nanophotonic device for use in quantum communication and quantum optics-based information processing. Sören Kreinberg et al. proposed a concept for a compact resonantly driven single-photon source by performing quantum-optical spectroscopy of a two-level system using a compact high-β micro-laser as the excitation source [20]. In this paper, the energy eigenvalues and the quantum efficiency of a micro-laser system includes a QD embedded in the different micro-cavities were investigated. In fact, in this work, the effect of different micro-cavities on the quantum efficiency of this nanophotonic device has been investigated. Then, the optimal value of the micro-cavity decay rate was obtained to achieve the maximum quantum efficiency.

2. QUANTUM MODEL

The micro-laser system consists of an array of quantum dots embedded in the micro-cavity, is an array of quantum dots in coupling with the micro-cavity. The CQED model in the Heisenberg picture is usually used to describe these quantum optic systems. The equations (1)-(4) represent the equations of motion for this system [24-26].

$$dp/dt = \alpha n_e + \alpha n_h + \alpha n_p \left(n_e + n_h - 1\right) - p\left(\kappa + \gamma\right) \tag{1}$$

$$dn_p/dt = 2Re\left(p\right) N_{QD} - 2n_p \kappa \tag{2}$$

$$dn_e/dt = \frac{\eta P\left(1 - n_e\right)}{\hbar\omega_p} - 2Re\left(p\right) n_e - \gamma_{nl} n_h n_e - \gamma_{nr} n_e \tag{3}$$

$$E_{1,2} = \frac{E_c + E_a}{2} - i\frac{\kappa + \gamma_a}{4} \mp \sqrt{\alpha^2 - \frac{\left(\kappa - \gamma_a - 2i\Delta\right)^2}{16}} \tag{4}$$

Where, p, n_p, n_e and n_h are polarization, photon population, electron and hole population, respectively. γ, κ, γ_{nl}, γ_{nr} and N_{QD} are the dephasing rate, cavity decay rate, spontaneous emission rate into non-lasing modes, non-radiative carrier-loss rate and number of QDs, respectively. In equations (3) and (4), P is laser pump power, η is carrier injection efficiency and $\hbar\omega_p$ is photon energy. In [27], the theoretical details of this quantum model are discussed. QDs are nearly ideal two-level systems [20], so we study this quantum optical problem for a QD within a micro-cavity and consider this QD to be a two-level atom system. In quantum mechanics, $H_a = E_g \left|\mathrm{g}\right> \left<\mathrm{g}\right| + E_e \left|\mathrm{e}\right> \left<\mathrm{e}\right|$ is the Hamiltonian of a two-level atom system. Considering $\left|g\right> = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ and $\left|e\right> = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and Pauli's matrix, $H_a = \frac{1}{2}\hbar\omega_0\sigma_z$. By semi-classical approach, the Hamiltonian of interaction for this quantum photonic system is equation (5).

$$H_{int} = \hbar\left(\alpha\Lambda^+ + \alpha^*\Lambda^-\right)\left(a - a^\dagger\right) \tag{5}$$

Where α is the coherent interaction rate between the quantum emitter (which in this case is QD) and micro-cavity, a and $a^{\dagger}$ are the annihilation and creation operators and Λ^{+} and Λ^{-} are the equations (6) and (7).

$$\Lambda^{+}=|e><g|=\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix} \tag{6}$$

$$\Lambda^{-}=|g><e|=\begin{pmatrix}0 & 0\\ 1 & 0\end{pmatrix} \tag{7}$$

By applying the rotating wave approximation to the Hamiltonian of interaction, the following equation is obtained:

$$H_{int}=\hbar\left(\alpha\Lambda^{+}a+\alpha^{*}\Lambda^{-}a^{\dagger}\right) \tag{8}$$

Finally, the total Hamiltonian equals equation (9).

$$H_{total}=\frac{1}{2}\hbar\omega_0\sigma_z+\hbar\omega aa^{\dagger}+\hbar\left(\alpha\Lambda^{+}+\alpha^{*}\Lambda^{-}\right)\left(a-a^{\dagger}\right) \tag{9}$$

Using total Hamiltonian in the Schrödinger equation, Energy eigen-values of this quantum optical system becomes equation (10).

$$E_{1,2}=\frac{E_c+E_a}{2}-i\frac{\kappa+\gamma_a}{4}\mp\sqrt{\alpha^2-\frac{\left(\kappa-\gamma_a-2i\Delta\right)^2}{16}} \tag{10}$$

Where Δ is detuning, E_a and E_c are the atom and micro-cavity energies, κ and γ_a are the cavity and atom decay rates. At resonance state ($E_a=E_c$), the variations of Energy eigen-values (ΔE) is equation (11).

$$\Delta E=\sqrt{4\left(\alpha^2-\frac{\left(\kappa-\gamma_a\right)^2}{16}\right)} \tag{11}$$

The quantum efficiency of this quantum optical system for the case where QD with micro-cavity is in a strong coupling regime, is obtained by equation (12) [25]

$$\eta=\frac{4\alpha^2/\gamma_a\kappa}{1+4\alpha^2/\gamma_a\kappa}\frac{\kappa}{\gamma_a+\kappa} \tag{12}$$

3. RESULTS AND DISCUSSION

At the first step, the energy eigenvalues variations for the micro-laser including a QD with a decay rate of 0.8μeV within different micro-cavity with coherent interaction rates of 35, 55, 75 and 95μeV were calculated. The results are shown in figure (2).

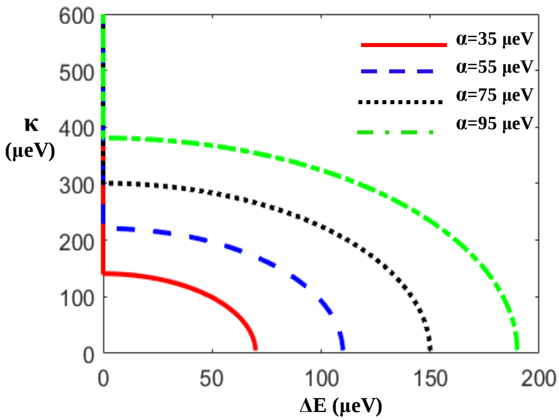

Figure 2. Energy eigenvalues variations versus decay rate of micro-cavity for different coherent interaction rates

The results show that with the increasing coherent interaction rate of the micro-laser system, the energy eigenvalues variations of this optical system also increase. For such micro-lasers with coherent interaction rates of 35, 55, 75, and 95, the energy eigenvalues variations start for micro-cavities with decay rates of 142.1, 223.8, 302, and 381μeV.

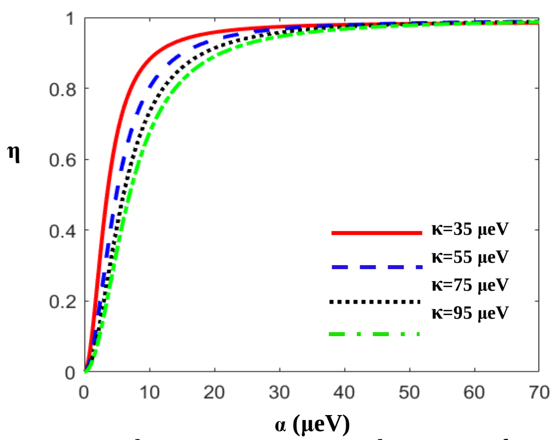

Figure 3. Energy eigenvalues variations versus decay rate of micro-cavity for different coherent interaction rates

At the second step, the quantum efficiency of a micro-laser system includes a QD with a decay rate of 0.8μeV embedded in the four micro-cavities was investigated.

As figure (3) shows, in this micro-laser system, the smaller micro-cavity decay rate, the higher quantum efficiency at smaller coherent interaction rate. Then, the optimal value of the micro-cavity decay rate was obtained in order to achieve the maximum quantum efficiency. This optimization was performed for the micro-laser system, including a QD with γ_a=0.8μeV in the different micro-cavities with coherent interaction rates of 35, 55, 75, and 95μeV (figure (4)).

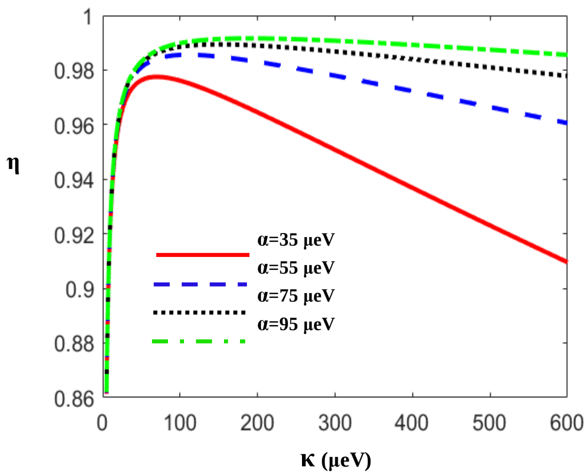

Figure 4. Quantum efficiency versus decay rate of micro-cavity for different coherent interaction rates

The calculation results showed that maximum quantum efficiency of this micro-laser for coherent interaction rates of 35, 55, 75 and 95μeV, can be achieved at micro-cavity decay rates of 71.26μeV (η_{max}=0.977), 120.5μeV (η_{max}=0.985), 159.2μeV (η_{max}=0.989) and 177.7μeV (η_{max}=0.991), respectively. Therefore, the highest quantum efficiency occurs for optical parameters γ_a=0.8μeV, g=95μeV, γ_c=177.7μeV and η_{max}=0.991. Table (1) shows the calculation results to achieve maximum quantum efficiency at different coherent interaction rates.

Finally, different QDs were embedded in the micro-laser with coherent interaction rates of 60μeV to achieve the maximum quantum efficiency, optimum value of micro-cavity decay rate was obtained. These results are shown in figure (5)

Table 1.
The calculation results to achieve maximum quantum efficiency at different α

γ_a (μeV)	α (μeV)	Optimum value of κ (μeV)	η_{max}
0.8	35	**71.26**	**0.977**
0.8	55	**120.5**	**0.985**
0.8	75	**159.2**	**0.989**
0.8	95	**177.7**	**0.991**

Finally, different QDs were embedded in the micro-laser with coherent interaction rates of 60μeV to achieve the maximum quantum efficiency, optimum value of micro-cavity decay rate was obtained. These results are shown in figure (5)

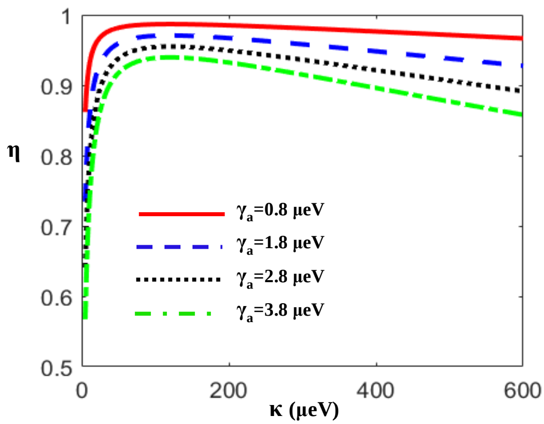

Figure 5. Quantum efficiency versus decay rate of micro-cavity for different QD decay rates

As the results show, maximum quantum efficiency of this micro-laser for coherent interaction rates of 60μeV and QD decay rates of 0.8, 1.8, 2.8 and 3.8μeV can be achieved at micro-cavity decay rates of 104.4μeV (η_{max}=0.987), 107.7μeV (η_{max}=0.971), 122.1μeV (η_{max}=0.954) and 123.3μeV (η_{max}=0.939), respectively. Therefore, the highest quantum efficiency occurs for optical parameters g=60μeV, γ_a=0.8μeV, γ_c=104.4μeV and η_{max}=0.987. Table (2) shows the calculation results to achieve maximum quantum efficiency at different QD decay rates.

Table 2.
The calculation results to achieve maximum quantum efficiency at different γ_a

α (μeV)	γ_a (μeV)	Optimum value of κ (μeV)	η_{max}
60	0.8	**<u>104.4</u>**	**<u>0.987</u>**
60	1.8	**107.6**	**0.971**
60	2.8	**122.1**	**0.954**
60	3.8	**123.3**	**0.939**

4. CONCLUSIONS

A micro-laser system includes a QD embedded in the different micro-cavities was studied. The results show that with increasing coherent interaction rate of this system, its energy eigenvalues variations also increase. In addition, the smaller micro-cavity decay rate, the higher quantum efficiency at smaller coherent interaction rate. The calculation results showed that maximum quantum efficiency of this micro-laser for coherent interaction rates of 35, 55, 75 and 95μeV, can be achieved at micro-cavity decay rates of 71.26μeV (η_{max}=0.977), 120.5μeV (η_{max}=0.985), 159.2μeV (η_{max}=0.989) and 177.7μeV (η_{max}=0.991), respectively. Therefore, the highest quantum efficiency occurs for optical parameters γ_a=0.8μeV, g=95μeV, γ_c=177.7μeV and η_{max}=0.991.

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